

## IV. RESULTS

We successfully tested 28 fuel/stove combinations, three times each. The methods and results of primary measurements are found in **Appendices E & F**. Here we derive instant emissions ratios and K-factors, power levels, efficiencies, carbon balances and ultimate K-factors, and emission factors.

### A. Emission Ratios

Gross and net concentrations of pollutants in the fluegas of fuel/stove combinations are presented in **Appendix F** along with a discussion of the cross-laboratory comparison for quality control the resulting corrections applied to the data. **Table 3** shows the resulting instant ratios to CO<sub>2</sub>. Also shown are the instant K-values.

According to the Indian standard for domestic LPG stoves, the limit for CO/CO<sub>2</sub> emission ratio is 0.02 (BIS, 1984). This ratio provides a simply measured indicator of combustion quality and this limit is thought to keep the risk of acute CO poisoning to acceptable levels. In our experiments, the mean CO/CO<sub>2</sub> ratios for biogas, LPG, and kerosene wick stoves are below this limit. The ratios for all biofuels and charcoal are much higher than this value. The highest CO/CO<sub>2</sub> ratio is found for charcoal. These are the same results as found in the Manila pilot study (Smith *et al.* 1992; 1993).

The CO emission ratio for wood varied from 0.03 to 0.17. The higher emission ratio 0.17 was recorded for wood in the improved mud stove. The CO emission ratios for the two wood species in traditional mud and three-rock stove are between 0.03 and 0.04. Hao *et al.* (1990) reported the CO emission ratio for wood stoves as 0.06 for open combustion over a range of biomass types. This discrepancy may be due to the difference in measurement techniques, particularly in that Hao *et al.* were not able to monitor all carbon outputs, which would tend to inflate the apparent CO emission ratios.

The range of CO emission ratios (0.14-0.16) for the improved vented mud stove (ivm) is much higher than the CO emission ratio for some of improved mud stoves (between 0.04 and 0.07) reported in FAO (1993); whereas the range of CO emission ratios for wood fuel in the improved vented ceramic stove (ivc) is within this range (0.03-0.6). The CO emission ratio for wood in the improved unvented metal stove (imet), is the same (0.04) as given in FAO (1993). Clearly, because of the large differences that occur with changes in design, more effort is needed to identify exactly which aspects of stove design affect these ratios.

The CO emission ratios for dungcake and crop residues are higher than the ratios for wood fuel in all types of stoves tested. This is similar to the findings of the earlier study by FAO. Except for dungcake, all other tested fuels produced a CO ratio higher in the ivm stove. In general, our N<sub>2</sub>O/CO<sub>2</sub> ratios are lower than the 0.007 quoted by Crutzen and Andreae (1990), who, however, did not monitor small-scale combustion devices directly.

Table 3. Instant emission ratios and nominal combustion efficiencies (NCE) for all tests.  
(K = sum of ratios of all carbon in all airborne products of incomplete combustion to carbon in CO<sub>2</sub>)

| <i>Fuel-Stove</i> | <i>CO/CO<sub>2</sub></i> | <i>CH<sub>4</sub>/CO<sub>2</sub></i> | <i>TNMOC/CO<sub>2</sub></i> | <i>TSP/CO<sub>2</sub></i> | <i>K-Instant</i> | <i>NCE= 1/(1+k)</i> |
|-------------------|--------------------------|--------------------------------------|-----------------------------|---------------------------|------------------|---------------------|
| <b>Gas</b>        |                          |                                      |                             |                           |                  |                     |
| LPG               | 6.3 0 E-3                | 1.27E-5                              | 0.0186                      | 5.77E-4                   | 0.0255           | 0.975               |
| LPG               | 9.34E-3                  | 1.21E-4                              | 0.0156                      | 5.46E-4                   | 0.0256           | 0.975               |
| LPG               | 7.24E-3                  | 5.72E-6                              | 0.0105                      | 7.10E-4                   | 0.0185           | 0.982               |
| Biogas            | 2.05E-3                  | 3.46E-4                              | 4.22E-4                     | 3.73E-4                   | 0.00319          | 0.997               |
| Biogas            | 3.00E-3                  | 0.00524                              | 0.00207                     | 0.00146                   | 0.0118           | 0.988               |
| Biogas            | 1.34E-3                  | 2.02E-4                              | 3.97E-4                     | 4.05E-5                   | 0.00198          | 0.998               |
| <b>Kerosene</b>   |                          |                                      |                             |                           |                  |                     |
| kero-pres         | 0.0350                   | 0.00120                              | 0.0125                      | 6.12E-4                   | 0.0494           | 0.953               |
| kero-pres         | 0.0380                   | 0.00107                              | 0.0180                      | 1.05E-3                   | 0.0581           | 0.945               |
| kero-pres         | 0.0267                   | 7.40E-4                              | 0.0174                      | 9.67E-4                   | 0.0459           | 0.956               |
| kero-wick         | 6.69E-3                  | 1.20E-4                              | 0.0122                      | 9.06E-4                   | 0.0109           | 0.981               |
| kero-wick         | 0.0109                   | 4.09E-4                              | 0.0131                      | 2.67E-4                   | 0.0246           | 0.976               |
| kero-wick         | 0.0100                   | 2.59E-4                              | 0.0108                      | 4.63E-4                   | 0.0215           | 0.979               |
| <b>Charfuel</b>   |                          |                                      |                             |                           |                  |                     |
| Charcoal          | 0.197                    | 0.0128                               | 0.00938                     | 0.00318                   | 0.222            | 0.818               |
| Charcoal          | 0.201                    | 0.00680                              | 0.0131                      | 0.00474                   | 0.226            | 0.816               |
| Charcoal          | 0.143                    | 0.00762                              | 0.00949                     | 0.00151                   | 0.162            | 0.861               |
| Charbriq          | 0.135                    | 0.00749                              | 0.0301                      | 0.00516                   | 0.177            | 0.849               |
| Charbriq          | 0.103                    | 0.00562                              | 0.0268                      | 0.00373                   | 0.139            | 0.878               |
| Charbriq          | 0.121                    | 0.0146                               | 0.0174                      | 0.00105                   | 0.154            | 0.867               |
| <b>Wood</b>       |                          |                                      |                             |                           |                  |                     |
| Acacia-imet       | 0.0465                   | 0.00968                              | 0.0169                      | 0.0122                    | 0.0853           | 0.921               |
| Acacia-imet       | 0.0409                   | 0.00784                              | 0.0174                      | 0.00700                   | 0.0731           | 0.932               |
| Acacia-imet       | 0.0393                   | 0.00626                              | 0.0245                      | 0.0175                    | 0.0875           | 0.920               |
| Acacia-ivc        | 0.0232                   | 0.00741                              | 0.0361                      | 0.0145                    | 0.0813           | 0.925               |
| Acacia-ivc        | 0.0236                   | 0.00356                              | 0.0305                      | 0.0129                    | 0.0706           | 0.934               |
| Acacia-ivc        | 0.0392                   | 0.00575                              | 0.0290                      | 0.0115                    | 0.0855           | 0.921               |
| Acacia-ivm        | 0.152                    | 0.0290                               | 0.0362                      | 0.0158                    | 0.233            | 0.811               |
| Acacia-ivm        | 0.131                    | 0.0346                               | 0.0297                      | 0.00959                   | 0.205            | 0.830               |
| Acacia-ivm        | 0.142                    | 0.0374                               | 0.0288                      | 0.0108                    | 0.219            | 0.820               |
| Acacia-3R         | 0.0359                   | 0.0174                               | 0.0209                      | 0.00483                   | 0.0791           | 0.927               |
| Acacia-3R         | 0.0342                   | 0.0211                               | 0.0163                      | 0.00440                   | 0.0759           | 0.929               |
| Acacia-3R         | 0.0387                   | 0.0286                               | 0.0209                      | 0.00823                   | 0.0965           | 0.912               |
| Acacia-tm         | 0.0397                   | 0.0103                               | 0.0128                      | 0.00111                   | 0.0639           | 0.940               |
| Acacia-tm         | 0.0288                   | 0.00598                              | 0.0161                      | 0.00235                   | 0.0533           | 0.949               |
| Acacia-tm         | 0.0351                   | 0.00590                              | 0.0154                      | 0.00258                   | 0.059            | 0.944               |

(continued)

Table 3 (continued)

| <i>Fuel-Stove</i>    | <i>CO/CO<sub>2</sub></i> | <i>CH<sub>4</sub>/CO<sub>2</sub></i> | <i>TNMOC/CO<sub>2</sub></i> | <i>TSP/CO<sub>2</sub></i> | <i>K-Instant</i> | <i>NCE= 1/(1+k)</i> |
|----------------------|--------------------------|--------------------------------------|-----------------------------|---------------------------|------------------|---------------------|
| Eucal-imet           | 0.0356                   | 0.00289                              | 0.0439                      | 0.00789                   | 0.090            | 0.917               |
| Eucal-imet           | 0.0543                   | 0.00967                              | 0.0284                      | 0.00547                   | 0.098            | 0.911               |
| Eucal-imet           | 0.0525                   | 0.00772                              | 0.0175                      | 0.00365                   | 0.081            | 0.925               |
| Eucal-ivc            | 0.0638                   | 0.0169                               | 0.0388                      | 0.00711                   | 0.127            | 0.888               |
| Eucal-ivc            | 0.0907                   | 0.00265                              | 0.0133                      | 0.00691                   | 0.114            | 0.898               |
| Eucal-ivc            | 0.0358                   | 0.00924                              | 0.00162                     | 0.00358                   | 0.050            | 0.952               |
| Eucal-ivm            | 0.166                    | 0.0298                               | 0.0632                      | 0.00977                   | 0.269            | 0.788               |
| Eucal-ivm            | 0.144                    | 0.0233                               | 0.0451                      | 0.00487                   | 0.218            | 0.821               |
| Eucal-ivm            | 0.156                    | 0.0419                               | 0.0884                      | 0.00996                   | 0.296            | 0.771               |
| Eucal-3R             | 0.0316                   | 0.00300                              | 0.0117                      | 0.00207                   | 0.048            | 0.954               |
| Eucal-3R             | 0.0401                   | 0.00627                              | 0.0168                      | 0.00164                   | 0.065            | 0.939               |
| Eucal-3R             | 0.0281                   | 0.00322                              | 0.0113                      | 0.00204                   | 0.045            | 0.957               |
| <b>Rootfuel</b>      |                          |                                      |                             |                           |                  |                     |
| root-ivm             | 0.0370                   | 0.00314                              | 0.0367                      | 0.0143                    | 0.091            | 0.917               |
| root-ivm             | 0.0439                   | 0.00599                              | 0.0308                      | 0.00487                   | 0.086            | 0.921               |
| root-ivm             | 0.0494                   | 0.00738                              | 0.0251                      | 0.00557                   | 0.087            | 0.920               |
| root-imet            | 0.0416                   | 0.00331                              | 0.00744                     | 0.00307                   | 0.055            | 0.947               |
| root-imet            | 0.0642                   | 0.00629                              | 0.0285                      | 0.00202                   | 0.101            | 0.908               |
| root-imet            | 0.0475                   | 0.00550                              | 0.0163                      | 0.00169                   | 0.071            | 0.934               |
| root-tm              | 0.0246                   | 0.0239                               | 0.0252                      | 0.00320                   | 0.077            | 0.929               |
| root-tm              | 0.0205                   | 0.00250                              | 0.0268                      | 0.000615                  | 0.050            | 0.952               |
| root-tm              | 0.0474                   | 0.0320                               | 0.0205                      | 0.00221                   | 0.102            | 0.907               |
| <b>Crop Residues</b> |                          |                                      |                             |                           |                  |                     |
| must-ivm             | 0.158                    | 0.0421                               | 0.0614                      | 0.0136                    | 0.275            | 0.784               |
| must-ivm             | 0.0972                   | 0.111                                | 0.0790                      | 0.0119                    | 0.299            | 0.770               |
| must-ivm             | 0.158                    | 0.0423                               | 0.0517                      | 0.0126                    | 0.265            | 0.791               |
| must-ivc             | 0.0505                   | 0.00646                              | 0.0333                      | 0.00831                   | 0.099            | 0.910               |
| must-ivc             | 0.0889                   | 0.0140                               | 0.0883                      | 0.0205                    | 0.212            | 0.825               |
| must-ivc             | 0.0928                   | 0.0148                               | 0.0543                      | 0.0129                    | 0.175            | 0.851               |
| must-imet            | 0.0558                   | 0.00731                              | 0.0273                      | 0.00791                   | 0.098            | 0.910               |
| must-imet            | 0.0945                   | 0.0122                               | 0.0348                      | 0.00338                   | 0.145            | 0.873               |
| must-imet            | 0.0469                   | 0.00425                              | 0.00744                     | 0.00670                   | 0.065            | 0.939               |
| must-tm              | 0.0762                   | 0.0199                               | 0.0335                      | 0.00163                   | 0.131            | 0.884               |
| must-tm              | 0.108                    | 0.0204                               | 0.00730                     | 0.00196                   | 0.138            | 0.879               |
| must-tm              | 0.0555                   | 0.00830                              | 0.00732                     | 0.00175                   | 0.073            | 0.932               |
| rice-ivm             | 0.288                    | 0.00916                              | 0.0200                      | 0.0590                    | 0.376            | 0.727               |
| rice-ivm             | 0.0921                   | 0.0111                               | 0.0200                      | 0.105                     | 0.228            | 0.814               |
| rice-ivm             | 0.117                    | 0.0151                               | 0.0200                      | 0.0113                    | 0.164            | 0.859               |
| rice-tm              | 0.0865                   | 0.0126                               | 0.0192                      | 0.00221                   | 0.121            | 0.892               |
| rice-tm              | 0.0785                   | 0.0224                               | 0.0246                      | 0.00298                   | 0.129            | 0.886               |
| rice-tm              | 0.0448                   | 0.00584                              | 0.0189                      | 0.00286                   | 0.072            | 0.932               |

(continued)

Table 3 (continued)

| <i>Fuel-Stove</i> | <i>CO/CO<sub>2</sub></i> | <i>CH<sub>4</sub>/CO<sub>2</sub></i> | <i>TNMOC/CO<sub>2</sub></i> | <i>TSP/CO<sub>2</sub></i> | <i>K-Instant</i> | <i>NCE= 1/(1+k)</i> |
|-------------------|--------------------------|--------------------------------------|-----------------------------|---------------------------|------------------|---------------------|
| <b>Dung</b>       |                          |                                      |                             |                           |                  |                     |
| dung-ivc          | 0.0367                   | 0.00740                              | 0.0653                      | 0.00622                   | 0.116            | 0.896               |
| dung-ivc          | 0.0696                   | 0.0148                               | 0.0935                      | 0.00959                   | 0.188            | 0.842               |
| dung-ivc          | 0.0377                   | 0.00646                              | 0.0646                      | 0.00591                   | 0.115            | 0.897               |
| dung-tm           | 0.0709                   | 0.0128                               | 0.0483                      | 0.00703                   | 0.139            | 0.878               |
| dung-tm           | 0.0835                   | 0.0187                               | 0.0450                      | 0.00409                   | 0.151            | 0.869               |
| dung-tm           | 0.0737                   | 0.0145                               | 0.0410                      | 0.00627                   | 0.136            | 0.881               |
| dung-ivm          | 0.0362                   | 0.00693                              | 0.0589                      | 0.00508                   | 0.107            | 0.903               |
| dung-ivm          | 0.0607                   | 0.0140                               | 0.0804                      | 0.00702                   | 0.162            | 0.861               |
| dung-ivm          | 0.0383                   | 0.00457                              | 0.0645                      | 0.00496                   | 0.112            | 0.899               |
| dung-hara         | 0.132                    | 0.123                                | 0.0551                      | 0.00181                   | 0.311            | 0.763               |
| dung-hara         | 0.0987                   | 0.0226                               | 0.0736                      | 0.00249                   | 0.197            | 0.835               |
| dung-hara         | 0.0720                   | 0.0128                               | 0.0466                      | 0.00190                   | 0.133            | 0.882               |

## B. Power and Thermal Efficiency

Thermal performance measured as power input and overall thermal efficiency ( $\eta$ ) of various stove fuel combinations tested were calculated according to the methodology described in **Appendix D**. We did not attempt to change the power in different experiments except those due to interventions in the fire to ensure a steady flame. The power input and efficiency values for three experiments for each fuel/stove combination were averaged and given in **Tables 4 and 5**.

The tables show that the power input of the stoves tested ranged from 1.3 kW for kerosene wick stove to 7.6 kW for mustard stalk in traditional stoves. The average power inputs for the stoves burning gaseous and liquid fuels were low, 1.3- 1.7 kW. For solid fuels the power inputs varied from 1.6 kW for char briquettes in Angethi to 7.6 kW for mustard stalks in traditional stoves. Compared with the improved stoves, the traditional stove had high power in all of the fuel categories. Among various fuels tested the power-input increases from gaseous fuel and kerosene to wood, and charcoal to dung cake to crop residues (**Figure 4**), generally in line with the energy ladder framework (Smith 1990; OTA 1992).

Table 4. Power input and thermal efficiency for gaseous and liquid fuels

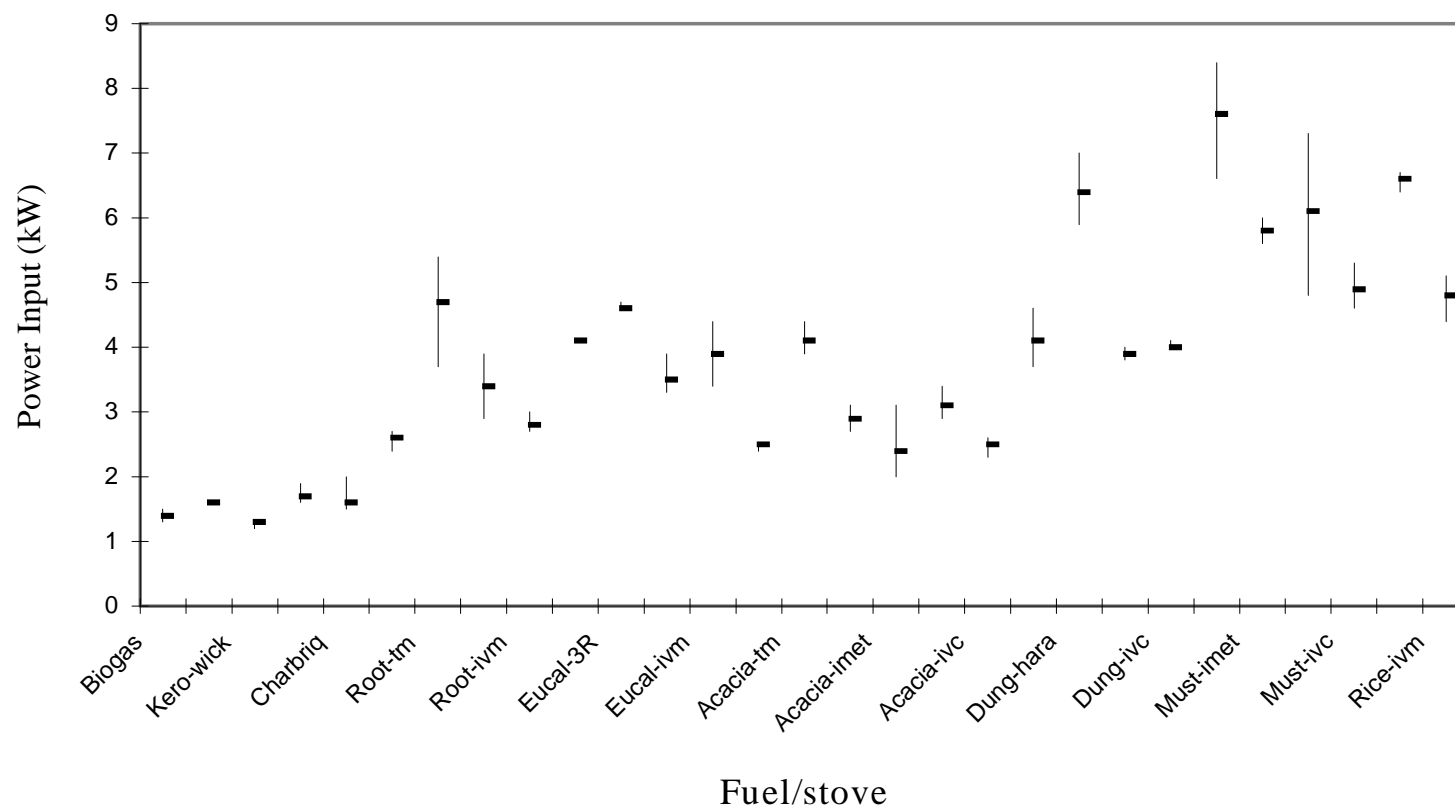
| <i>Fuel/stove</i> | <i>Power kW</i> | <i>Efficiency % (<math>\eta</math>)</i> |
|-------------------|-----------------|---|
| LPG               | 1.6 $\pm$ (0.1) | 53.6 $\pm$ (2.2)                        |
| Biogas            | 1.4 $\pm$ (0.1) | 57.3 $\pm$ (0.5)                        |
| Kerosene/wick     | 1.3 $\pm$ (0.1) | 50.0 $\pm$ (6.7)                        |
| Kerosene/pressure | 1.7 $\pm$ (0.1) | 47.0 $\pm$ (2.2)                        |

Table 5. Power input and thermal efficiency for solid fuels

| <i>Fuel-stove</i> | <i>Power kW</i> | <i>Efficiency % (<math>\eta</math>)</i> |
|-------------------|-----------------|---|
| Acacia-ivc        | $2.5 \pm (0.2)$ | $29.0 \pm (1.9)$                        |
| Eucal-ivc         | $2.5 \pm (0.1)$ | $28.7 \pm (1.0)$                        |
| Acacia-imet       | $2.4 \pm (0.6)$ | $25.7 \pm (2.5)$                        |
| Acacia-ivm        | $3.1 \pm (0.2)$ | $23.5 \pm (2.2)$                        |
| Root-imet         | $3.4 \pm (0.5)$ | $22.8 \pm (1.2)$                        |
| Eucal-ivm         | $3.9 \pm (0.5)$ | $22.0 \pm (1.8)$                        |
| Must-imet         | $5.8 \pm (0.2)$ | $21.7 \pm (1.6)$                        |
| Eucal-imet        | $3.5 \pm (0.3)$ | $21.4 \pm (1.8)$                        |
| Root-ivm          | $2.8 \pm (0.5)$ | $19.7 \pm (1.3)$                        |
| Must-ivc          | $4.9 \pm (0.4)$ | $18.5 \pm (0.8)$                        |
| Acacia-tm         | $4.1 \pm (0.2)$ | $18.2 \pm (0.6)$                        |
| Acacia-3 rock     | $2.9 \pm (0.2)$ | $18.1 \pm (0.6)$                        |
| Eucal-3 rock      | $4.6 \pm (0.1)$ | $17.7 \pm (0.3)$                        |
| Charcoal          | $2.6 \pm (0.2)$ | $17.5 \pm (2.7)$                        |
| Eucal-tm          | $4.1 \pm (0.0)$ | $16.7 \pm (0.7)$                        |
| Charbriquette     | $1.6 \pm (0.3)$ | $16.4 \pm (0.5)$                        |
| Root-tm           | $4.7 \pm (0.9)$ | $14.2 \pm (1.8)$                        |
| Must-ivm          | $6.1 \pm (1.2)$ | $13.5 \pm (0.5)$                        |
| Dung-ivc          | $4.0 \pm (0.1)$ | $12.8 \pm (1.0)$                        |
| Must-tm           | $7.6 \pm (1.0)$ | $12.4 \pm (1.0)$                        |
| Rice-ivm          | $4.8 \pm (0.4)$ | $10.9 \pm (1.0)$                        |
| Dung-ivm          | $3.9 \pm (0.1)$ | $10.0 \pm (0.2)$                        |
| Rice-tm           | $6.6 \pm (0.2)$ | $9.8 \pm (1.1)$                         |
| Dung-tm           | $4.1 \pm (0.5)$ | $9.4 \pm (0.6)$                         |
| Dung-hara         | $6.4 \pm (0.6)$ | $8.2 \pm (1.3)$                         |

(Standard Deviation of three tests shown)

Figure 4. Power input for various fuel/stove combinations



The average thermal efficiency ( $\eta$ ) of the biogas stove (57.3%) is the highest among all stoves tested. Khadi and Village Industries Commission (KVIC) and Bureau of Indian Standards (BIS) recommend that the efficiency of domestic biogas burner should not be less than 55%. A report of KVIC states that a thermal efficiency of 59.5% could be obtained for the corresponding power of 1.61kW (Kishore and Dhingra 1990), quite close to our average efficiency of 57.3% for the corresponding power of 1.59 kW. The average efficiency of the LPG stove is 53.6%, which is less than the BIS specification of 60% (BIS-4246 1984). The kerosene wick stove had the efficiency of 50% and the average efficiency of kerosene pressure stove was 47%. The efficiency of the kerosene wick stove is less than the efficiency of 57% reported previously (TERI 1987). In addition, previous studies have sometimes found that the pressure stove is more efficient, unlike our finding.<sup>3</sup>

The efficiency of Angethi (17.5%) with charcoal is comparable to that (15.3%) quoted by Wazir (1981). The average efficiency of traditional stoves with various biomass fuels varied from 9.4 to 18.2%, being low for dungcake and high for wood. Wazir (1981) reported the efficiencies of the traditional stove vary from 5 to 20%. George (1997) found the efficiency of traditional mud stove to average 17.9%. The average efficiency of the 3-rock stove was also about 18% which is within the efficiency range (12-24%) reported in TERI (1987).

The efficiencies of the improved stoves were higher than that of the traditional and 3-rock stoves. The improved vented ceramic (ivc) had high efficiency for all fuels except crop residues. The average efficiencies of the improved vented mud stove (ivm - *Nada chulha*) across fuels varied from 10% to 23.5%, which is compatible with the range reported by Pal and Joshi (1989) of 10.8% to 19.6%. Our measurements using wood fuels in the improved unvented stove (*Priyagni* - imet) of 21.4 & 25.7% are compatible with the 26% reported by FAO (1993). Among various fuels, dungcake had the lowest efficiency in all stoves, being lowest of all in the Hara stove (8.2%).

**Tables 4 and 5** show that the overall thermal efficiency ( $\eta$ ) increases by moving up the energy ladder from dungcake to crop residue to wood to kerosene to gas. This pattern is similar to the typical energy ladder of South Asia discussed by Smith *et al.* (1994).

Overall stove thermal efficiency was determined by the method outlined in Appendix D, i.e. dividing the calorific value of the fuel used in a test run into the heat absorbed by the water in the pot during the same run. It is a linear combination of two internal efficiencies:

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<sup>3</sup> It is useful to note in this context, however, that the standard deviation of the kero-wick stove efficiencies was high in our experiments (COV = 13%, Table 3), indicating no statistically significant difference between the two kerosene stoves in overall efficiency ( $\eta$ ).

$$\eta = \text{NCE} * \text{HTE} \quad (14)$$

NCE (nominal combustion efficiency) is the percentage of the chemical energy in the fuel that is actually released and is defined here as the percentage of airborne fuel carbon released as CO<sub>2</sub>

$$\text{NCE} = 1/(\text{K}+1) - \text{see Equations (1-3)} \quad (15)$$

Instant NCEs are shown in the last column of Table 3. HTE (nominal heat transfer efficiency) is the percentage of heat released by combustion that is absorbed by the water in the pot. This was not measured directly in our experiments and is determined using Equation 14, since both NCE and  $\eta$  are available from the tests.

From an environmental point of view, the two most important parameters are  $1/(1-\text{NCE})$  which is a direct indicator of how much PIC pollution is released and  $\eta$  which indicates the amount of fuel used. To ease comparisons, we will frequently summarize our main results by fuel/stove combination using the ranking derived by application of an Environmental Stove Index (ESI) that is composed of these two parameters:

$$\text{ESI} = \ln[\eta/(1-\text{NCE})] \quad (16)$$

As shown in **Figure 5**, HTE and NCE each trends downward with ESI, although the differences between stove designs cause some deviations.

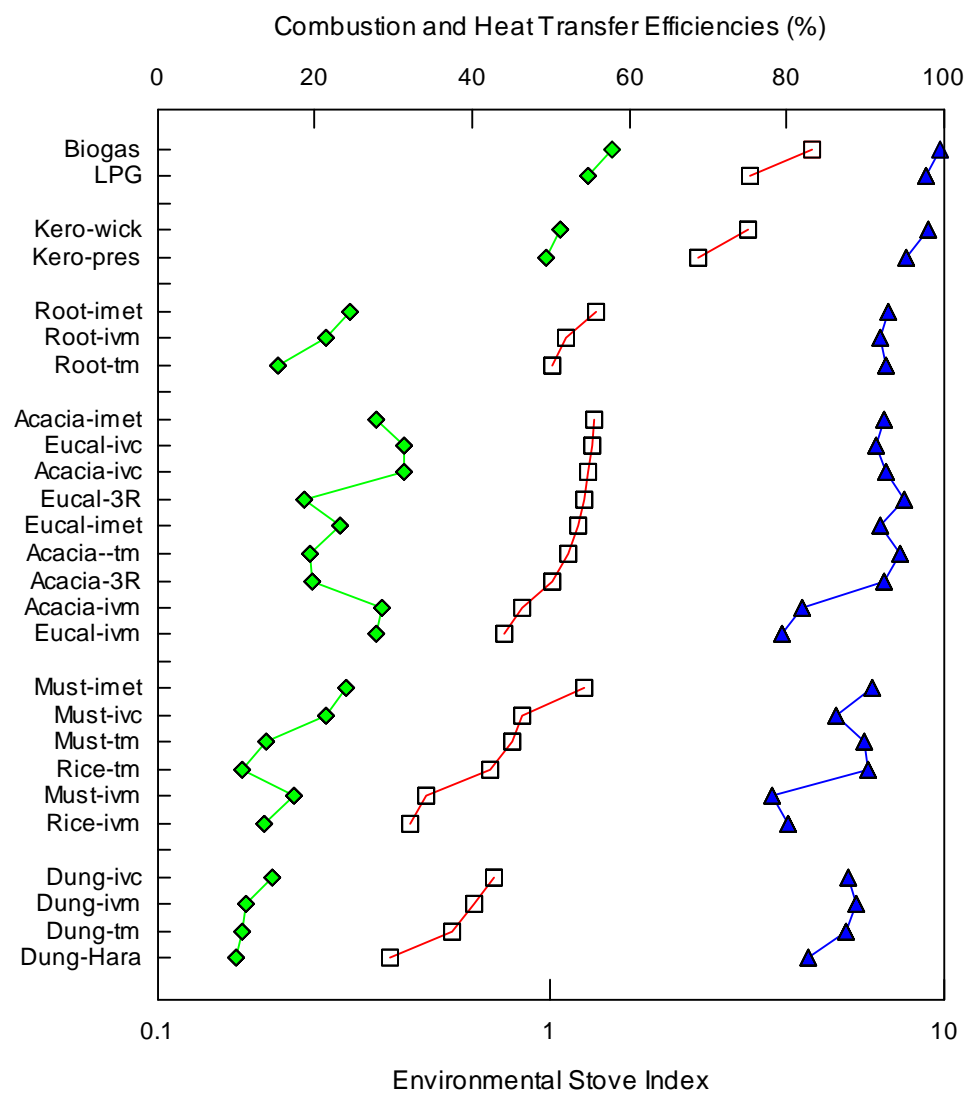
The average overall efficiency of fuel/stove combinations decreases with increasing average power levels in a nonlinear way (**Figure 6**). Biogas, LPG, and kerosene stoves burned at low power with high efficiencies, the reverse of dungcake and crop residues.

The relative performance of stove types is shown in **Figure 7**. Note the relatively good performance of the improved metal stove (imet) compared to the other two improved stoves. The other two, however, are vented, which would presumably reduce indoor pollution levels. It is interesting also that the simplest stove in the world, the three-rock stove (3R) is a better performer than most of the improved stoves tested.

### C. Carbon Balances

**Table 6** shows the gross carbon balances per unit fuel carbon of each fuel/stove combination. The first columns are for instant combustion, as in **Figure 3a**. The second set of column show the ultimate values, which represent the total of processes in **Figures 3a and 3b**. The two are the same for kerosene and gaseous fuels because they produce no char and the same for dung and crop residues because they produce char of too low quality to burn. Also shown are the ultimate K-factors and NCEs.

**Figure 5. ESI and Instant Combustion and Heat Transfer Efficiencies**  
Along the Household Energy Ladder



□ Environmental Stove Index (lower axis) 
 ◆ Nominal Heat Transfer Efficiency 
 ▲ Nominal Combustion Efficiency

**Figure 6. Power Input Vs Efficiency**

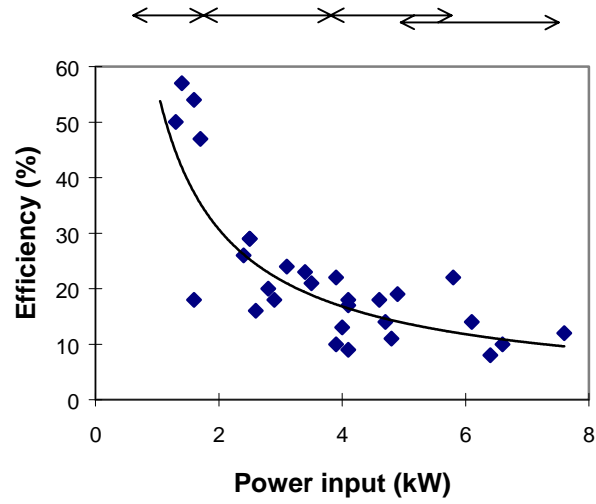


Figure 7. Major Efficiencies and ESI by Stove Type  
Unprocessed Biomass Fuels

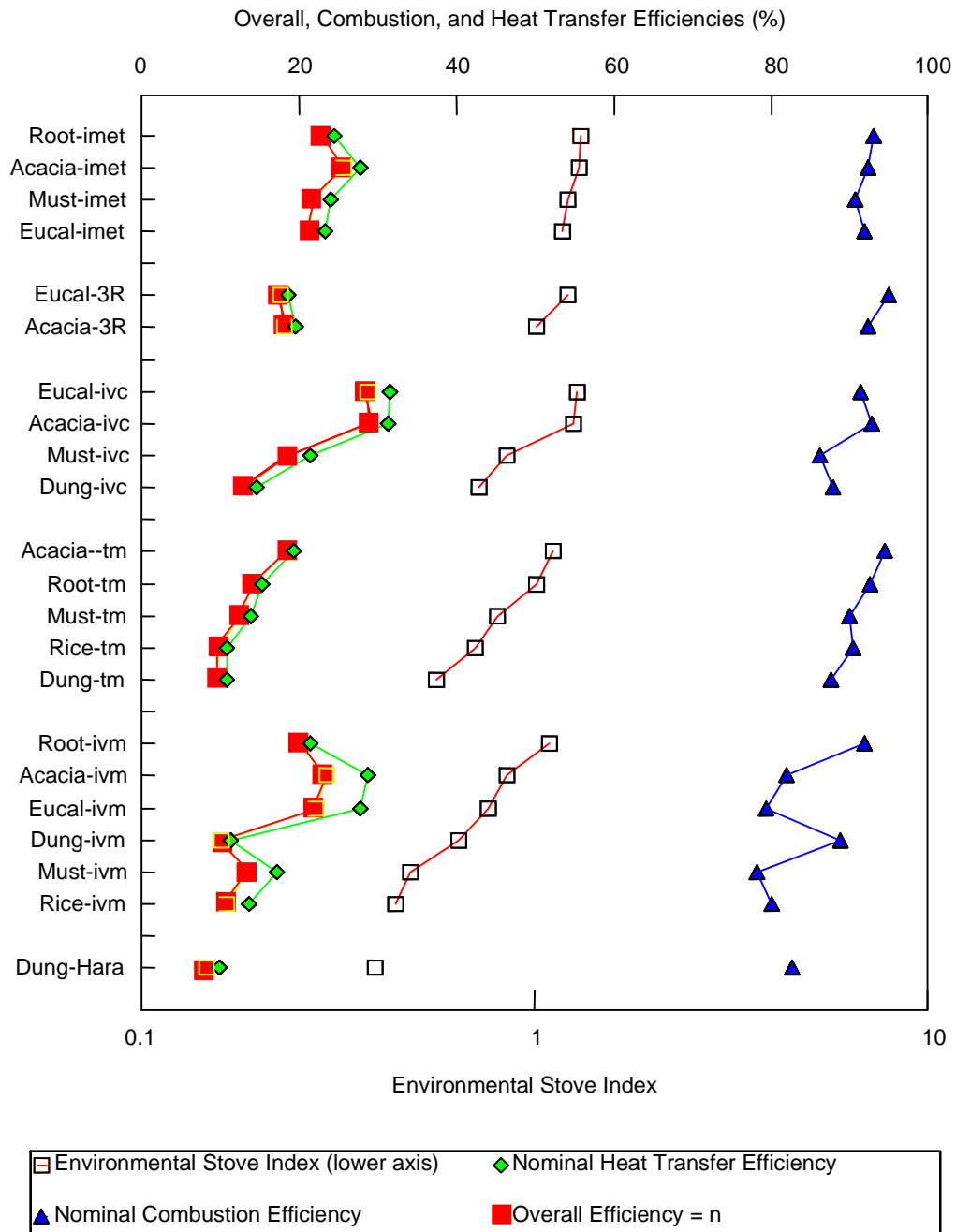


Table 6. Gross instant and ultimate carbon balances; grams carbon based on 1.0 kilogram fuel input. (See Figure 3.) The two measures are the same except for wood and root fuels. Ultimate K-factors, nominal combustion efficiencies (NCEs), and heat transfer efficiencies (HTEs) are also shown.

| <i>Fuel/stove</i> | <i>Instant</i> |          |                 |      |       | <i>Ultimate</i> |                 |      |       | <i>K-factor</i> | <i>NCE</i> | <i>HTE</i> |
|-------------------|----------------|----------|-----------------|------|-------|-----------------|-----------------|------|-------|-----------------|------------|------------|
|                   | Fuel           | Char/ash | CO <sub>2</sub> | PIC  | TSP   | Char/ash        | CO <sub>2</sub> | PIC  | TSP   |                 |            |            |
| LPG               | 860            | 0        | 841.4           | 19.0 | 0.514 |                 |                 |      |       | 0.0231          | 0.978      | 0.548      |
| Biogas            | 396            | 0        | 393.8           | 1.97 | 0.247 |                 |                 |      |       | 0.00562         | 0.995      | 0.577      |
| Kero-pressure     | 843            | 0        | 802.6           | 40.2 | 0.699 |                 |                 |      |       | 0.0510          | 0.951      | 0.494      |
| Kero-wick         | 843            | 0        | 825.5           | 17.7 | 0.449 |                 |                 |      |       | 0.0220          | 0.978      | 0.511      |
| Charcoal          | 800            | 9.93     | 657.5           | 131  | 2.05  |                 |                 |      |       | 0.202           | 0.831      | 0.210      |
| Charbriq          | 503            | 0.601    | 434.7           | 66.4 | 1.43  |                 |                 |      |       | 0.156           | 0.861      | 0.190      |
| Eucal-imet        | 454            | 76.9     | 345.8           | 29.1 | 1.96  | 0.954           | 409.0           | 41.7 | 2.16  | 0.107           | 0.902      | 0.237      |
| Eucal-ivm         | 454            | 157      | 236.2           | 59.4 | 1.90  | 1.94            | 364.9           | 85.0 | 2.32  | 0.239           | 0.807      | 0.273      |
| Eucal-ivc         | 454            | 130      | 295.9           | 26.5 | 1.71  | 1.62            | 402.9           | 47.8 | 2.09  | 0.124           | 0.889      | 0.323      |
| Eucal-3R          | 454            | 98.9     | 337.6           | 17.1 | 0.644 | 1.23            | 418.9           | 33.2 | 0.936 | 0.0815          | 0.924      | 0.191      |
| Acacia-tm         | 418            | 130      | 272.7           | 15.4 | 0.558 | 1.61            | 379.5           | 36.6 | 0.888 | 0.0988          | 0.910      | 0.200      |
| Acacia-imet       | 418            | 102      | 291.3           | 20.3 | 3.54  | 1.26            | 375.1           | 37.0 | 3.84  | 0.109           | 0.902      | 0.285      |
| Acacia-ivm        | 418            | 169      | 204.8           | 42.4 | 2.56  | 2.09            | 343.6           | 70.0 | 3.02  | 0.212           | 0.824      | 0.285      |
| Acacia-ivc        | 418            | 189      | 213.0           | 14.0 | 2.78  | 2.34            | 368.0           | 44.9 | 3.35  | 0.131           | 0.884      | 0.328      |
| Acacia-3R         | 418            | 120      | 276.0           | 21.6 | 1.63  | 1.49            | 374.8           | 41.2 | 1.97  | 0.115           | 0.896      | 0.202      |
| Root-tm           | 518            | 56.4     | 428.7           | 31.8 | 0.857 | 0.699           | 475.1           | 41.1 | 1.02  | 0.0886          | 0.917      | 0.155      |
| Root-imet         | 518            | 74.5     | 412.4           | 30.3 | 0.912 | 0.924           | 473.6           | 42.5 | 1.12  | 0.0921          | 0.915      | 0.249      |
| Root-ivm          | 518            | 110      | 376.1           | 30.0 | 3.09  | 1.36            | 466.3           | 47.9 | 3.36  | 0.110           | 0.921      | 0.219      |
| Must-tm           | 421            | 26.2     | 355.1           | 39.4 | 0.631 |                 |                 |      |       | 0.113           | 0.898      | 0.138      |
| Must-imet         | 421            | 15.0     | 368.7           | 35.3 | 2.22  |                 |                 |      |       | 0.102           | 0.907      | 0.239      |
| Must-ivm          | 421            | 48.2     | 291.5           | 77.6 | 3.71  |                 |                 |      |       | 0.279           | 0.781      | 0.173      |
| Must-ivc          | 421            | 62.0     | 309.5           | 45.3 | 4.26  |                 |                 |      |       | 0.160           | 0.861      | 0.215      |
| Rice-tm           | 381            | 49.2     | 300.3           | 31.2 | 0.802 |                 |                 |      |       | 0.106           | 0.903      | 0.108      |
| Rice-ivm          | 381            | 46.0     | 268.1           | 51.8 | 14.9  |                 |                 |      |       | 0.249           | 0.769      | 0.136      |
| Dung-tm           | 334            | 14.4     | 280.1           | 38.1 | 1.61  |                 |                 |      |       | 0.142           | 0.822      | 0.107      |
| Dung-ivm          | 334            | 7.07     | 290.5           | 35.2 | 1.63  |                 |                 |      |       | 0.126           | 0.887      | 0.113      |
| Dung-ivc          | 334            | 9.56     | 285.3           | 37.4 | 2.03  |                 |                 |      |       | 0.138           | 0.877      | 0.146      |
| Dung-hara         | 334            | 12.9     | 265.6           | 55.0 | 0.545 |                 |                 |      |       | 0.209           | 0.824      | 0.099      |

## D. Ultimate Emission Factors

Emission factors were estimated separately for the three experiments in each fuel/stove combination and the results expressed as an average of the three experiments done for each. Three types of ultimate emission factors are presented here:<sup>4</sup>

- Emission factors per kilogram fuel in pollutant mass ( $E_{f_m}$ ): **Table 7**
- Emission factors per kilogram fuel in pollutant carbon mass ( $E_{f_m}$ ): **Table 7**
- Emission factors per MJ net energy in fuel ( $E_{f_e}$ ): **Table 8**
- Emission factors per MJ delivered energy ( $E_{f_d}$ ): **Table 8**

$E_{f_d}$  is based on 1.0 MJ delivered to the pot and thus takes into account the energy efficiency of the stove. Although there is obviously much variation throughout the nation, 1.0 MJ delivered represents a typical amount of energy used to cook a household meal.

The appropriate type of emission factor to use depends on the policy question being asked. Here, we start with a discussion of emissions factors per unit fuel mass.

The CO<sub>2</sub> emission factor by fuel mass is high for LPG due to the high carbon content in the fuel (about 86%) and good combustion efficiency of the stove, which lead to high CO<sub>2</sub> and less PIC (products of incomplete combustion - CO, CH<sub>4</sub>, TNMOC).

The CO emission factor is high for charcoal (275 g/kg) and low for biogas (2 g/kg), reflecting relative NCEs. CO emission factors for *eucalyptus* varies from 26-85 g/kg, with those from the three-rock stove being at the low end. For rootfuel and rice straw, the emission factors for improved stoves are also higher than the traditional stoves, a finding consistent with Ahuja *et al.* (1987). Increased emission factors for “improved” stoves is consistent with previous evidence that design changes directed at improving efficiency can actually increase emission factors for many pollutants (TERI 1985). This is because they generally work to increase NTE, but in the process lower NCE.

CH<sub>4</sub> emission factors are low for gases and kerosene, but quite high for crop residues in improved stoves. Among the three improved stoves, in most of the cases the emission factor is high for the ivm stoves and lower for ivc stoves. Comparatively, the efficiency is higher in ivc, which may be due to the ceramic lining and the firebox design that helps in proper airflow and in turn enhances NCE.

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<sup>4</sup> As discussed in **Appendix F**, because of canister shipping problems, no N<sub>2</sub>O data are available for rootfuel and dung. Consequently, we have estimated the N<sub>2</sub>O emissions by extrapolation from the measured wood and crop residue emissions and relative N content in the fuels, as explained in the footnotes to **Table 7**.

Table 7. Ultimate emissions by fuel mass on a pollutant mass basis (g/kg) and on a carbon mass basis (g-C/kg)

| <i>Fuel-Stove</i> | <i>K-factor</i> | <i>By Pollutant Mass (g/kg)</i> |       |                 |        |                  |        | <i>By Pollutant Carbon Mass (g-C/kg)</i> |        |                 |        |                  |        |
|-------------------|-----------------|---------------------------------|-------|-----------------|--------|------------------|--------|--|--------|-----------------|--------|------------------|--------|
|                   |                 | CO <sub>2</sub>                 | CO    | CH <sub>4</sub> | TNMOC  | N <sub>2</sub> O | TSP    | CO <sub>2</sub>                          | CO     | CH <sub>4</sub> | TNMOC  | N <sub>2</sub> O | TSP    |
| Biogas            | 0.0056          | 1444                            | 1.950 | 1.005           | 0.5670 | 0.0950           | 0.5250 | 393.8                                    | 0.8357 | 0.7538          | 0.3780 | 0.0605           | 0.2470 |
| LPG               | 0.023           | 3085                            | 14.93 | 0.0500          | 18.78  | 0.1470           | 0.5140 | 841.4                                    | 6.399  | 0.0375          | 12.52  | 0.0935           | 0.5140 |
| Kero-wick         | 0.022           | 3027                            | 17.65 | 0.2880          | 14.86  | 0.0790           | 0.5160 | 825.5                                    | 7.564  | 0.2160          | 9.907  | 0.0503           | 0.4490 |
| Kero-pres         | 0.051           | 2943                            | 62.10 | 1.071           | 19.20  | 0.1020           | 0.7010 | 802.6                                    | 26.61  | 0.8033          | 12.80  | 0.0649           | 0.6990 |
| Root-imet         | 0.092           | 1737                            | 74.68 | 3.501           | 11.77  | 0.4764           | 1.176  | 473.6                                    | 32.01  | 2.626           | 7.847  | 0.3032           | 1.123  |
| Acacia-imet       | 0.109           | 1373                            | 63.61 | 4.111           | 9.777  | 0.2765           | 3.811  | 374.5                                    | 27.26  | 3.083           | 6.518  | 0.1760           | 3.839  |
| Eucal-ivc         | 0.124           | 1477                            | 87.96 | 5.051           | 9.436  | 0.1722           | 2.107  | 402.9                                    | 37.70  | 3.788           | 6.290  | 0.1096           | 2.088  |
| Acacia-ivc        | 0.131           | 1349                            | 79.04 | 3.422           | 12.621 | 0.2048           | 3.320  | 368.0                                    | 33.88  | 2.566           | 8.414  | 0.1303           | 3.349  |
| Must-imet         | 0.102           | 1352                            | 55.97 | 3.840           | 12.65  | 0.1620           | 2.224  | 368.7                                    | 23.99  | 2.880           | 8.433  | 0.1031           | 2.224  |
| Eucal-3R          | 0.082           | 1536                            | 60.15 | 2.833           | 7.982  | 0.0728           | 0.9416 | 418.9                                    | 25.78  | 2.125           | 5.321  | 0.0463           | 0.9358 |
| Eucal-imet        | 0.107           | 1500                            | 64.71 | 3.883           | 16.60  | 0.1922           | 2.463  | 409.0                                    | 27.73  | 2.912           | 11.06  | 0.1223           | 2.156  |
| Acacia--tm        | 0.099           | 1391                            | 66.47 | 3.936           | 7.762  | 0.0921           | 1.038  | 379.5                                    | 28.49  | 2.952           | 5.174  | 0.0586           | 0.8880 |
| Root-ivm          | 0.110           | 1710                            | 75.89 | 3.864           | 18.76  | 0.4470           | 3.969  | 466.3                                    | 32.52  | 2.898           | 12.50  | 0.2845           | 3.364  |
| Acacia-3R         | 0.115           | 1374                            | 64.70 | 9.399           | 9.653  | 0.1782           | 2.054  | 374.8                                    | 27.73  | 7.049           | 6.435  | 0.1134           | 1.974  |
| Root-tm           | 0.089           | 1742                            | 49.98 | 11.69           | 16.30  | 0.4890           | 1.040  | 475.1                                    | 21.42  | 8.766           | 10.87  | 0.3112           | 1.021  |
| Must-ivc          | 0.160           | 1135                            | 55.34 | 4.792           | 26.92  | 0.1770           | 4.251  | 309.5                                    | 23.72  | 3.594           | 17.95  | 0.1126           | 4.258  |
| Acacia-ivm        | 0.212           | 1260                            | 125.8 | 10.79           | 11.94  | 0.1929           | 3.001  | 343.6                                    | 53.92  | 8.093           | 7.961  | 0.1227           | 3.022  |
| Must-tm           | 0.113           | 1302                            | 65.57 | 7.580           | 8.487  | 0.0490           | 0.6310 | 355.1                                    | 28.10  | 5.685           | 5.658  | 0.0312           | 0.6310 |
| Charbriq          | 0.156           | 1594                            | 120.6 | 5.335           | 16.13  | 0.1590           | 2.859  | 434.7                                    | 51.68  | 4.001           | 10.75  | 0.1012           | 1.431  |
| Eucal-ivm         | 0.239           | 1338                            | 139.1 | 11.45           | 25.13  | 0.1592           | 2.532  | 364.9                                    | 59.63  | 8.589           | 16.75  | 0.1013           | 2.324  |
| Dung-ivc          | 0.138           | 1046                            | 31.62 | 3.580           | 31.68  | 0.3140           | 2.050  | 285.3                                    | 13.55  | 2.685           | 21.12  | 0.1998           | 2.032  |
| Charcoal          | 0.202           | 2411                            | 275.1 | 7.906           | 10.48  | 0.2410           | 2.375  | 657.5                                    | 117.9  | 5.930           | 6.987  | 0.1534           | 2.049  |
| Rice-tm           | 0.106           | 1101                            | 48.70 | 5.390           | 9.390  | 0.2200           | 0.8050 | 300.3                                    | 20.87  | 4.043           | 6.260  | 0.1400           | 0.8020 |
| Dung-ivm          | 0.126           | 1065                            | 30.31 | 3.250           | 29.49  | 0.3190           | 1.645  | 290.5                                    | 12.99  | 2.438           | 19.66  | 0.2030           | 1.631  |
| Dung-tm           | 0.142           | 1027                            | 49.58 | 5.700           | 18.81  | 0.3080           | 2.210  | 280.1                                    | 21.25  | 4.275           | 12.54  | 0.1960           | 1.609  |
| Must-ivm          | 0.279           | 1069                            | 94.10 | 24.92           | 27.87  | 0.1830           | 3.702  | 291.5                                    | 40.33  | 18.69           | 18.58  | 0.1165           | 3.707  |
| Rice-ivm          | 0.249           | 983.0                           | 101.0 | 4.240           | 8.036  | 0.1970           | 15.47  | 268.1                                    | 43.29  | 3.180           | 5.357  | 0.1254           | 14.85  |
| Dung-hara         | 0.209           | 974.0                           | 61.39 | 17.56           | 23.22  | 0.2920           | 0.5500 | 265.6                                    | 26.31  | 13.17           | 15.48  | 0.1858           | 0.5450 |

\*For those fuel-stove combinations where N<sub>2</sub>O measurements are missing, the emission ratios were extrapolated from those for the same fuel or the fuel with a similar nitrogen content.

Table 8. Ultimate emission factors of pollutant mass by fuel energy content (g/MJ) and delivered energy to pot (g/MJ-del)

| <i>Fuel-Stove</i> | <i>Energy</i><br>(kJ/kg) | <i>Overall</i><br>$E_{ff} = \eta$ | <i>By Fuel Energy (g/MJ)</i> |        |                 |        |                  |        | <i>By Delivered Energy (g/MJ-del)</i> |        |                 |        |                  |        |
|-------------------|--------------------------|-----------------------------------|------------------------------|--------|-----------------|--------|------------------|--------|---------------------------------------|--------|-----------------|--------|------------------|--------|
|                   |                          |                                   | CO <sub>2</sub>              | CO     | CH <sub>4</sub> | TNMOC  | N <sub>2</sub> O | TSP    | CO <sub>2</sub>                       | CO     | CH <sub>4</sub> | TNMOC  | N <sub>2</sub> O | TSP    |
| Biogas            | 17710                    | 0.574                             | 81.54                        | 0.1101 | 0.0567          | 0.0320 | 0.00536          | 0.0296 | 142.0                                 | 0.1918 | 0.0989          | 0.0558 | 0.00935          | 0.0516 |
| LPG               | 45840                    | 0.536                             | 67.30                        | 0.3257 | 0.00109         | 0.4097 | 0.00321          | 0.0112 | 125.6                                 | 0.6076 | 0.00203         | 0.7643 | 0.00598          | 0.0209 |
| Kero-wick         | 43120                    | 0.500                             | 70.20                        | 0.4093 | 0.0067          | 0.3446 | 0.00183          | 0.0120 | 140.4                                 | 0.8186 | 0.0134          | 0.6892 | 0.00366          | 0.0239 |
| Kero-pres         | 43120                    | 0.470                             | 68.25                        | 1.440  | 0.0248          | 0.4453 | 0.00237          | 0.0163 | 145.2                                 | 3.064  | 0.0528          | 0.9474 | 0.00503          | 0.0346 |
| Root-imet         | 15480                    | 0.228                             | 112.2                        | 4.824  | 0.2262          | 0.7604 | 0.0308           | 0.0760 | 492.0                                 | 21.16  | 0.9920          | 3.335  | 0.1350           | 0.3332 |
| Acacia-imet       | 15100                    | 0.257                             | 90.95                        | 4.213  | 0.2723          | 0.6475 | 0.0183           | 0.2524 | 353.9                                 | 16.39  | 1.059           | 2.519  | 0.0713           | 0.9820 |
| Eucal-ivc         | 15330                    | 0.287                             | 96.37                        | 5.738  | 0.3295          | 0.6155 | 0.0112           | 0.1374 | 335.8                                 | 19.99  | 1.148           | 2.145  | 0.0391           | 0.4788 |
| Acacia-ivc        | 15100                    | 0.290                             | 89.36                        | 5.235  | 0.2266          | 0.8358 | 0.0136           | 0.2199 | 308.2                                 | 18.05  | 0.7814          | 2.882  | 0.0468           | 0.7581 |
| Must-imet         | 16530                    | 0.217                             | 81.79                        | 3.386  | 0.2323          | 0.7653 | 0.00980          | 0.1345 | 376.9                                 | 15.60  | 1.071           | 3.527  | 0.0452           | 0.6200 |
| Eucal-3R          | 15330                    | 0.177                             | 100.2                        | 3.924  | 0.1848          | 0.5207 | 0.00475          | 0.0614 | 566.1                                 | 22.17  | 1.044           | 2.942  | 0.0268           | 0.3470 |
| Eucal-imet        | 15330                    | 0.214                             | 97.83                        | 4.221  | 0.2533          | 1.083  | 0.0125           | 0.1607 | 457.2                                 | 19.72  | 1.184           | 5.059  | 0.0586           | 0.7509 |
| Acacia--tm        | 15100                    | 0.182                             | 92.15                        | 4.402  | 0.2606          | 0.5140 | 0.00610          | 0.0687 | 506.3                                 | 24.19  | 1.432           | 2.824  | 0.0335           | 0.3776 |
| Root-ivm          | 15480                    | 0.197                             | 110.4                        | 4.902  | 0.2496          | 1.212  | 0.0289           | 0.2564 | 560.6                                 | 24.89  | 1.267           | 6.151  | 0.1466           | 1.301  |
| Acacia-3R         | 15100                    | 0.181                             | 91.01                        | 4.285  | 0.6224          | 0.6392 | 0.0118           | 0.1360 | 502.8                                 | 23.67  | 3.439           | 3.532  | 0.0652           | 0.7515 |
| Root-tm           | 15480                    | 0.142                             | 112.5                        | 3.229  | 0.7550          | 1.053  | 0.0316           | 0.0672 | 792.5                                 | 22.74  | 5.317           | 7.415  | 0.2225           | 0.4733 |
| Must-ivc          | 16530                    | 0.185                             | 68.66                        | 3.348  | 0.2899          | 1.629  | 0.0107           | 0.2572 | 371.2                                 | 18.10  | 1.567           | 8.803  | 0.0579           | 1.390  |
| Acacia-ivm        | 15100                    | 0.235                             | 83.43                        | 8.331  | 0.7146          | 0.7908 | 0.0128           | 0.1988 | 355.0                                 | 35.45  | 3.041           | 3.365  | 0.0543           | 0.8457 |
| Must-tm           | 16530                    | 0.124                             | 78.77                        | 3.967  | 0.4586          | 0.5134 | 0.00296          | 0.0382 | 635.2                                 | 31.99  | 3.698           | 4.141  | 0.0239           | 0.3078 |
| Charbriq          | 15930                    | 0.164                             | 100.1                        | 7.570  | 0.3349          | 1.013  | 0.0100           | 0.1795 | 610.1                                 | 46.16  | 2.042           | 6.174  | 0.0609           | 1.094  |
| Eucal-ivm         | 15330                    | 0.220                             | 87.28                        | 9.076  | 0.7471          | 1.639  | 0.0104           | 0.1652 | 396.7                                 | 41.26  | 3.396           | 7.452  | 0.0472           | 0.7507 |
| Dung-ivc          | 11760                    | 0.128                             | 88.95                        | 2.689  | 0.3044          | 2.694  | 0.0267           | 0.1743 | 694.9                                 | 21.01  | 2.378           | 21.05  | 0.2086           | 1.362  |
| Charcoal          | 25720                    | 0.175                             | 93.74                        | 10.70  | 0.3074          | 0.4075 | 0.0094           | 0.0923 | 535.7                                 | 61.13  | 1.756           | 2.328  | 0.0535           | 0.5277 |
| Rice-tm           | 13030                    | 0.098                             | 84.50                        | 3.738  | 0.4137          | 0.7206 | 0.0169           | 0.0618 | 862.2                                 | 38.14  | 4.221           | 7.354  | 0.1723           | 0.6304 |
| Dung-ivm          | 11760                    | 0.100                             | 90.56                        | 2.577  | 0.2764          | 2.507  | 0.0271           | 0.1399 | 905.6                                 | 25.77  | 2.764           | 25.07  | 0.2713           | 1.399  |
| Dung-tm           | 11760                    | 0.094                             | 87.33                        | 4.216  | 0.4847          | 1.599  | 0.0262           | 0.1879 | 929.0                                 | 44.85  | 5.156           | 17.02  | 0.2786           | 1.999  |
| Must-ivm          | 16530                    | 0.135                             | 64.67                        | 5.693  | 1.508           | 1.686  | 0.0111           | 0.2240 | 479.0                                 | 42.17  | 11.17           | 12.49  | 0.0820           | 1.659  |
| Rice-ivm          | 13030                    | 0.109                             | 75.44                        | 7.751  | 0.3254          | 0.6167 | 0.0151           | 1.187  | 692.1                                 | 71.11  | 2.985           | 5.658  | 0.1387           | 10.89  |
| Dung-hara         | 11760                    | 0.082                             | 82.82                        | 5.220  | 1.493           | 1.974  | 0.0248           | 0.0468 | 1010                                  | 63.66  | 18.21           | 24.08  | 0.3028           | 0.5704 |

The average emission factors ( $EF_m$ ) for various fuel/stove combinations are compared with other reported values in **Table 9**. It shows that the  $CO_2$ , CO and  $CH_4$  emission factors for LPG are comparable to the emission factors for LPG found in Manila Pilot study. But the TNMOC emission factor (19 g/kg) is much higher than reported in the Manila study. For kerosene wick the  $CO_2$ , TNMOC emission factors are close to the Manila study results. But CO and  $CH_4$  emission factors are less than the Manila study results.

The CO emission factor for the kerosene wick stove is even less than that reported by TERI (1987). For charcoal the  $CO_2$ , CO, &  $CH_4$  emission factors of the present study are comparable to the Manila study results, but TNMOC is higher. For fuelwood, the CO emission factors are lower than the CO emission factor 100 g/kg reported in the Manila study, but fall in the range of 13-68 reported by TERI (1987) and the range 17-130 reported by Smith (1987). CO emission factor for dungcake and crop residues are within the range reported by TERI (1987).

**Figures 8, 9, 10, and 11** show the emission factors by delivered energy ( $EF_i$ ) for  $CO_2$ , CO,  $CH_4$ , and TNMOC for various fuel/stove tested. Note the general agreement with the energy ladder framework (Smith 1990; OTA, 1992); i.e., that efficiency increases and emissions per meal decrease along a spectrum from solid to liquid to gaseous fuels.

## E. Comparison with IPCC Default Emission Factors

**Table 10** shows the default emission factors recommended by the IPCC (1997) for residential fuel use. As can be seen by comparison with **Table 7**, the IPCC values generally lie within the range of values found for various biomass-stove combinations in India. Compared to those for kerosene and LPG, however, the IPCC values for “oil” and natural gas, however, are substantially lower for CO, TNMOC, and  $N_2O$ , although being similar for methane. These differences indicate that the IPCC values are probably not suitable for use with these cooking fuels, at least under Indian conditions.

## F. Variation

To give an idea of the statistical variation, the COV for all  $Ef_m$  over the three separate test runs, are presented in **Table 11** (an error analysis is presented in **Appendix G**). Here are comments by pollutant:

- $CO_2$  emissions show little variation across all fuel/stove combinations tested, i.e.,  $COV < 0.1$ .
- CO emissions exhibit intermediate levels of variation, i.e.  $0.1 > COV < 0.4$ .
- $CH_4$  emissions show high COV (1.5) for the two gas stoves, probably because measured fluegas concentrations were near background levels and the equipment detection limits. Dung-hara exhibited a high COV (1.1) because one run had a particularly high level. All other fuel/stove combinations exhibit  $COV < 0.8$ , with most  $< 0.5$ .
- TNMOC emissions all have  $COV < 1.0$  with many  $< 0.3$ .
- $N_2O$  emissions exhibit four COV above 1.0 with most of the rest between 0.5 and 1.0.
- TSP emissions for biogas and charbriquette were above 1.0, but most others were below 0.5.

Table 9. Comparisons of emission factors (g/kg) by fuel mass with results from other studies

| <i>Fuel-stove</i> | <i>This Study</i> |     |                 |       |                  | <i>Manila Pilot Study Results (1)</i> |     |                 |       |                  | <i>TERI (2)</i> | <i>Other (3)</i> |
|-------------------|-------------------|-----|-----------------|-------|------------------|---------------------------------------|-----|-----------------|-------|------------------|-----------------|------------------|
|                   | CO <sub>2</sub>   | CO  | CH <sub>4</sub> | TNMOC | N <sub>2</sub> O | CO <sub>2</sub>                       | CO  | CH <sub>4</sub> | TNMOC | N <sub>2</sub> O | CO              | CO               |
| LPG               | 3085              | 15  | 0.05            | 18.8  | 0.15             | 3110                                  | 24  | 0.04            | 3     | 0.03             |                 |                  |
| Kero-wick         | 3027              | 18  | 0.3             | 14.8  | 0.08             | 3030                                  | 38  | 1               | 11    | 0.05             | 33-93           |                  |
| Charcoal          | 2411              | 275 | 7.9             | 10.5  | 0.24             | 2740                                  | 230 | 8               | 4     | 0.04             |                 |                  |
| Acacia-imet       | 1373              | 64  | 4.1             | 9.8   | 0.28             |                                       |     |                 |       |                  | 24-39           |                  |
| Acacia-tm         | 1391              | 66  | 3.9             | 7.8   | 0.09             | 1560                                  | 99  | 8               | 12    | 0.06             | 13-68           | 17-130           |
| Must-imet         | 1352              | 56  | 3.8             | 12.7  | 0.16             |                                       |     |                 |       |                  | 76-114          |                  |
| Dung-ivm          | 1065              | 30  | 3.3             | 29.5  | 0.32             |                                       |     |                 |       |                  | 26-67           |                  |

Source: <sup>1</sup>Smith et al., 1992

<sup>2</sup>TERI, 1987

<sup>3</sup>Smith, 1987

Table 10. IPCC default (uncontrolled) emission factors for residential fuel combustion (g/kg)

|                                       | <i>CO</i> | <i>CH<sub>4</sub></i> | <i>TNMOC</i> | <i>N<sub>2</sub>O</i> |
|---------------------------------------|-----------|-----------------------|--------------|-----------------------|
| Gas <sup>1</sup>                      | 2         | 0.2                   | 0.2          | 0.005                 |
| Oil <sup>2</sup>                      | 0.9       | 0.4                   | 0.2          | 0.03                  |
| Wood                                  | 80        | 5                     | 9            | 0.06                  |
| Charcoal                              | 200       | 6                     | 3            | 0.03                  |
| Dung/Agricultural Wastes <sup>3</sup> | 68        | 4                     | 8            | 0.05                  |

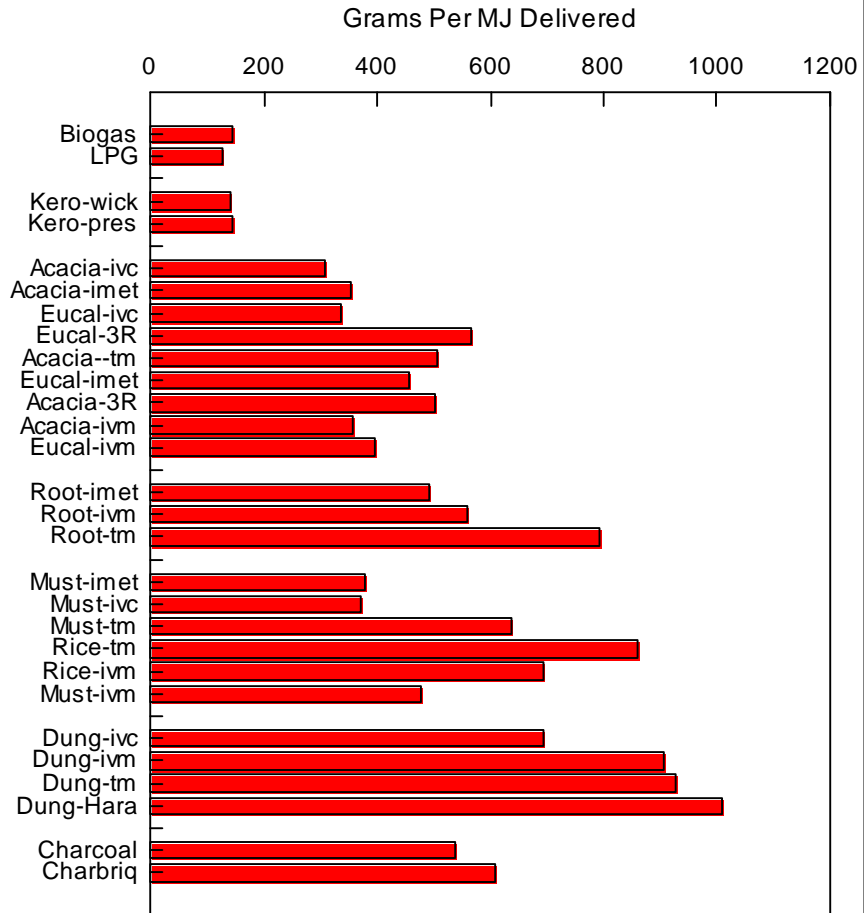
<sup>1</sup> Determined using the IPCC emission factors given for "Natural Gas" and the net calorific value given for "LPG"

<sup>2</sup> Determined using the IPCC emission factors given for "Oil" and the net calorific value given for "Other Kerosene"

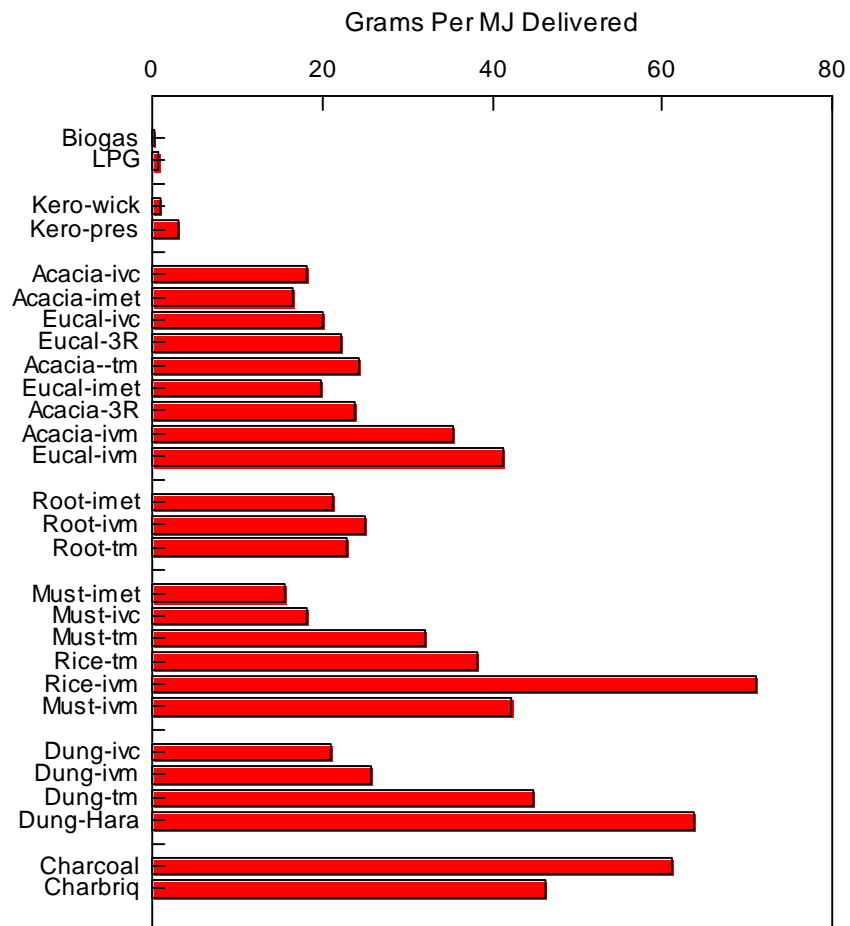
<sup>3</sup> Determined using the IPCC emission factors given for "Other Biomass and Wastes" and the average of the net calorific values given for "Dung" and "Agricultural Waste"

Source: IPCC, 1997

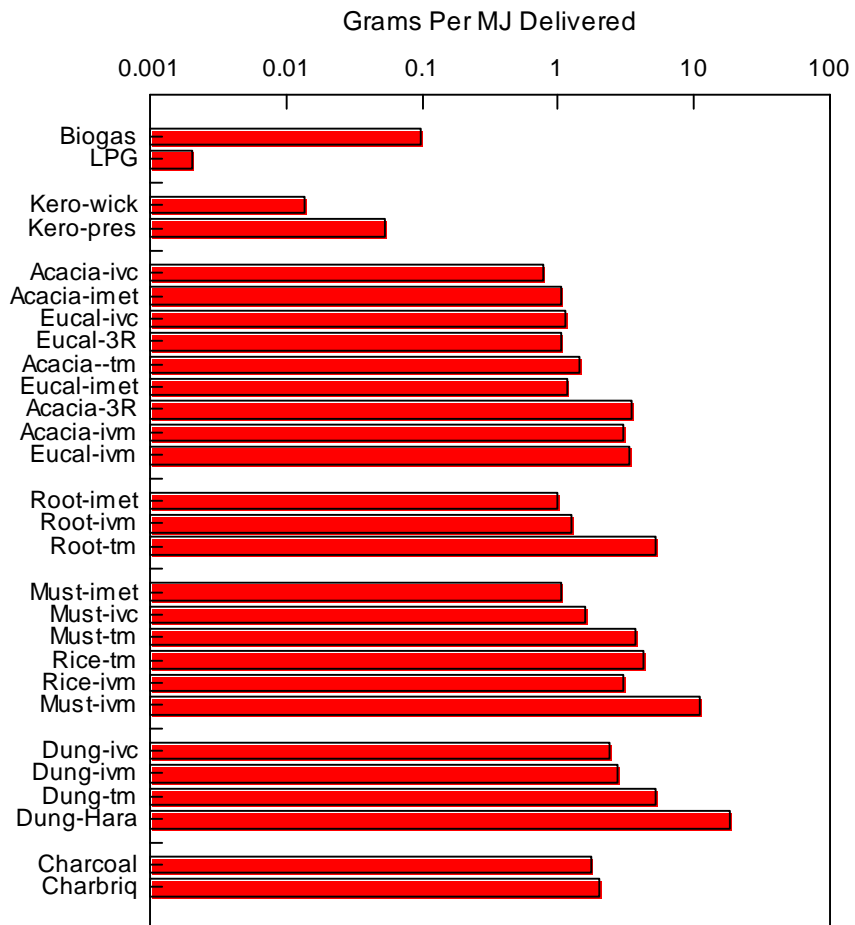
**Figure 8. Carbon Dioxide Emission Factors**  
Per MJ Delivered to the Pot



**Figure 9. Carbon Monoxide Emission Factors**  
Per MJ Delivered to the Pot



**Figure 10. Methane Emission Factors**  
Per MJ Delivered to the Pot



**Figure 11. TNMOC Emission Factors**  
Per MJ Delivered to the Pot

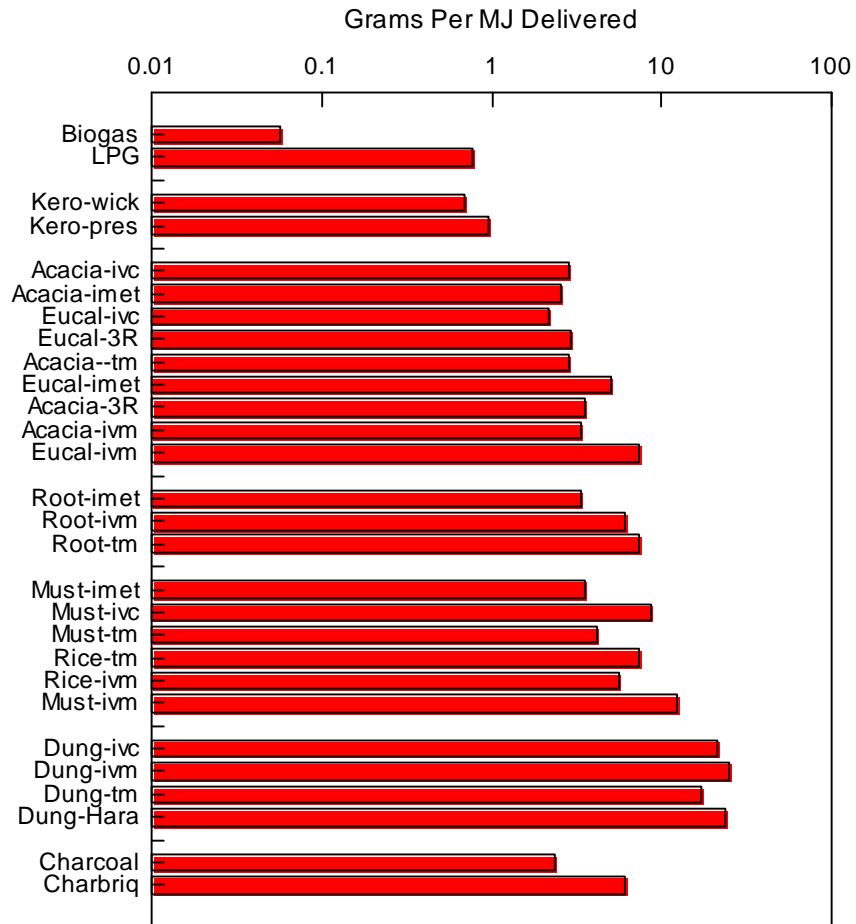


Table 11. Coefficients of variation (COV) for measurements for 3 tests of each fuel-stove combination

|               | $CO_2$ | $CO$  | $CH_4$ | $TNMOC$ | $TSP$ |
|---------------|--------|-------|--------|---------|-------|
| Biogas        | 0.017  | 0.41  | 1.49   | 1.01    | 1.26  |
| LPG           | 0.052  | 0.15  | 1.47   | 0.28    | 0.18  |
| Kero-wick     | 0.068  | 0.30  | 0.60   | 0.13    | 0.65  |
| Kero-pressure | 0.046  | 0.14  | 0.22   | 0.19    | 0.28  |
| Root-imet     | 0.042  | 0.27  | 0.34   | 0.64    | 0.33  |
| Acacia-imet   | 0.19   | 0.28  | 0.40   | 0.074   | 0.36  |
| Eucal-ivc     | 0.036  | 0.41  | 0.73   | 1.05    | 0.31  |
| Acacia-ivc    | 0.055  | 0.27  | 0.33   | 0.13    | 0.15  |
| Must-imet     | 0.019  | 0.40  | 0.53   | 0.62    | 0.38  |
| Eucal-3R      | 0.062  | 0.13  | 0.37   | 0.17    | 0.18  |
| Eucal-imet    | 0.076  | 0.26  | 0.56   | 0.43    | 0.18  |
| Acacia-tm     | 0.029  | 0.14  | 0.33   | 0.14    | 0.10  |
| Root-ivm      | 0.087  | 0.18  | 0.42   | 0.31    | 0.53  |
| Acacia-3R     | 0.034  | 0.10  | 0.29   | 0.16    | 0.36  |
| Root-tm       | 0.11   | 0.55  | 0.81   | 0.083   | 0.68  |
| Must-ivc      | 0.049  | 0.30  | 0.39   | 0.51    | 0.48  |
| Acacia-ivm    | 0.055  | 0.13  | 0.11   | 0.18    | 0.32  |
| Must-tm       | 0.059  | 0.36  | 0.42   | 0.89    | 0.15  |
| Charbriq      | 0.076  | 0.21  | 0.51   | 0.31    | 1.18  |
| Eucal-ivm     | 0.12   | 0.051 | 0.24   | 0.27    | 0.11  |
| Dung-ivc      | 0.087  | 0.35  | 0.44   | 0.20    | 0.26  |
| Charcoal      | 0.12   | 0.21  | 0.47   | 0.092   | 0.38  |
| Rice-tm       | 0.10   | 0.24  | 0.59   | 0.15    | 0.22  |
| Dung-ivm      | 0.009  | 0.30  | 0.57   | 0.16    | 0.20  |
| Dung-tm       | 0.013  | 0.09  | 0.20   | 0.09    | 0.16  |
| Must-ivm      | 0.046  | 0.29  | 0.57   | 0.17    | 0.091 |
| Rice-ivm      | 0.062  | 0.59  | 0.32   | 0.062   | 0.81  |
| Dung-Hara     | 0.077  | 0.22  | 1.10   | 0.24    | 0.21  |